

# Dense nuclear matter and symmetry energy in strong magnetic fields

Jianmin Dong<sup>1,2,3</sup>, Umberto Lombardo<sup>4</sup>, Wei Zuo<sup>1</sup>, Hongfei Zhang<sup>2</sup>

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1. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2. School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China
3. Graduate University of Chinese Academy of Sciences, Beijing 100049, China
4. Dipartimento di Fisica and INFN-LNS, Via S. Sofia 64, I-95123 Catania, Italy

## Abstract

The properties of nuclear matter in the presence of a strong magnetic field, including the density-dependent symmetry energy, the chemical composition and spin polarizations, are investigated in the framework of the relativistic mean field models FSU-Gold. The anomalous magnetic moments (AMM) of the particles and the nonlinear isoscalar-isovector coupling are included. It is found that the parabolic isospin-dependence of the energy per nucleon of asymmetric nuclear matter remains valid for values of the magnetic field below  $10^5 B_c^e$ ,  $B_c^e = 4.414 \times 10^{13} \text{G}$  being the electron critical field. Accordingly, the symmetry energy can be obtained by the difference of the energy per nucleon in pure neutron matter and that in symmetric matter. The symmetry energy, which is enhanced by the presence of the magnetic field, significantly affects the chemical composition and the proton polarization. The effects of the AMM of each component on the energy per nucleon, symmetry energy, chemical composition and spin polarization are discussed in detail.

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*Keywords:* nuclear matter; symmetry energy, strong magnetic field; anomalous magnetic moment, neutron stars

# 1 Introduction

Pulsars have been identified as rapidly rotating magnetized neutron stars, with a surface magnetic field as large as  $10^{11} - 10^{13}$  G [1]. It is currently assumed that soft gamma repeaters and anomalous X-ray pulsars have a strong surface magnetic fields, up to  $10^{14} - 10^{15}$  G [2]. The magnetic field in the interior could be as large as  $10^{18}$  G according to the scalar virial theorem [3]. The energy of a charged particle changes significantly if the magnetic field is comparable to or above a critical value. This critical field is defined as that value where the cyclotron energy is equal to the rest energy of the charged particle, which for electrons is  $B_c^e = 4.414 \times 10^{13}$  G. This value is usually taken as the unit of the strong magnetic field. In addition, the strong magnetic fields are also created in heavy-ion collisions. For example, in noncentral Au + Au collisions at 100 GeV/nucleon, the maximal magnetic field can reach about  $10^{17}$  G [4, 5]. The strong magnetic field is able to affect the dynamics of heavy ion reactions [6]. Therefore, one may expect considerable influence of such intense magnetic fields on the properties of neutron star matter and of neutron star, in particular the high density behavior of the symmetry energy.

Many investigations have been carried out on dense matter in strong magnetic fields, such as the equation of states [7–14], transport properties and the cooling or heating of magnetized stars [15–20]. The gross properties of cold symmetric matter and neutron star matter under the influence of strong magnetic fields were investigated in the relativistic Hartree theory in Ref. [7]. It was found that when the magnetic field is about  $10^{18}$  G and more, the nuclear matter in  $\beta$  equilibrium practically converts into the stable proton-rich matter. However, in these studies the effects of the anomalous magnetic moments (AMM) of nucleons were completely neglected. In Ref. [12], the authors based on relativistic mean field (RMF) models argued that an extremely strong magnetic field may lead to the pure neutron matter instead of the proton-rich matter when the nucleon AMM are included. This indicates the importance of the AMM effect. In addition, the structure of neutron stars can be significantly affected by the strong magnetic fields [21–24]. The magnetic field actually influences the neutron star structure in two ways: by modifying the energy density and pressure of the neutron star matter, and itself provides an additional energy density and pressure.

The energy per particle in nuclear matter is  $e(\rho, \beta) = e(\rho, 0) + S(\rho)\beta^2 + O(\beta^4)$  with the density  $\rho = \rho_n + \rho_p$  and asymmetry  $\beta = (\rho_n - \rho_p)/\rho$ . The density-dependent symmetry energy  $S(\rho)$  that characterizes the isospin-dependent part of the equation of state (EOS) of asymmetric nuclear matter plays a crucial role in understanding a variety of issues in nuclear physics as well as as-

trophysics, such as the heavy ion reactions [26–30], the stability of superheavy nuclei [31], and the structures, composition and cooling of neutron stars [25, 32–34]. Many theoretical and experimental efforts have been made to constrain the density-dependent symmetry energy. In this work, some properties of nuclear matter especially the symmetry energy and its effects in magnetic fields are investigated with a new relativistic mean field model proposed in Ref. [25]. And not only the AMM of nucleons but also the one of leptons are included, and the AMM of each component will be analyzed in detail. The electron AMM perhaps is important because it is larger than the proton and neutron magnetic moment owing to the large Bohr magneton with respect to nuclear magneton. The presence of a strong magnetic field could cause the polarization of nuclear matter, an issue recently investigated in many theoretical works [13, 35, 36].

This paper is organized as follows: In Section 2, a brief framework of the relativistic mean field model of the nuclear matter in a uniform magnetic field  $B$  is presented. Then the density dependent symmetry energy, fractions and spin polarization affected by the magnetic fields and AMM are shown in Sections 3, 4 and 5, respectively. Finally, a brief summary is provided in Section 6.

## 2 Brief framework of the method

In the RMF theory of nuclear matter that made of nucleons (p,n) and leptons (e,  $\mu$ ) in a uniform magnetic field  $B$  along the  $z$  axis, the total interacting Lagrangian density is given by

$$\begin{aligned}
\mathcal{L} = & \bar{\psi}_b(i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - \frac{1}{2}g_\rho\gamma^\mu\boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu \\
& - q_b\gamma^\mu\frac{1+\tau_3}{2}A_\mu - \frac{1}{4}\kappa_b\sigma_{\mu\nu}F^{\mu\nu})\psi_b - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - (\frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4) \\
& - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}g_\omega^2(\omega_\mu\omega^\mu)^2 \\
& + g_\omega\bar{\psi}\gamma^\mu\psi\omega_\mu + \Lambda_\nu g_\rho^2\rho_\mu \cdot \rho^\mu g_\omega^2\omega_\mu\omega^\mu \\
& - \frac{1}{4}\mathbf{R}_{\mu\nu} \cdot \mathbf{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu \cdot \rho^\mu \\
& + \bar{\psi}_l(i\gamma^\mu\partial_\mu - m_l - q_l\gamma^\mu A_\mu - \frac{1}{4}\kappa_l\sigma_{\mu\nu}F^{\mu\nu})\psi_l
\end{aligned} \tag{2.1}$$

with  $A^\mu = (0, 0, Bx, 0)$  and  $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ .  $\mu_N$  ( $\mu_B$ ) denotes the nuclear (Bohr) magneton of nucleons (leptons).  $\kappa_p = 1.7928\mu_N$ ,  $\kappa_n = -1.9130\mu_N$ ,  $\kappa_e = 1.15965 \times 10^{-3}\mu_B$  and  $\kappa_\mu = 1.16592 \times 10^{-3}\mu_B$  are the AMM for protons, neutrons, electrons and muons, respectively [37].  $M$ ,  $m_\sigma$ ,  $m_\omega$

and  $m_\rho$  are the nucleon-, the  $\sigma$ -, the  $\omega$ - and the  $\rho$ -meson masses, respectively. The nucleon field  $\psi_b$  interacts with the  $\sigma, \omega, \rho$  meson fields  $\sigma, \omega_\mu, \rho_\mu$  and with the photon field  $A_\mu$ . The field tensors for the vector meson are given as  $\Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$  and by similar expression for  $\rho$  meson and the photon. The self-coupling terms with coupling constants  $g_2$  and  $g_3$  for the  $\sigma$  meson are introduced because they turned out to be crucial [38]. Compared with the previous RMF models, the RMF interactions employed in this work is FSUGold where two additional parameters  $\zeta$  and  $\Lambda_\nu$  have been introduced:  $\omega$  meson self-interactions as described by  $\zeta$  which soften the equation of state at high density, and the nonlinear mixed isoscalar-isovector coupling described by  $\Lambda_\nu$  that modifies the density-dependence of the symmetry energy. The FSUGold interaction [25] gives a good description of ground state properties as well as excitations of finite nuclei.

The energy densities of proton, neutron, electron and muon are given by

$$\varepsilon_p = \frac{eB}{4\pi^2} \sum_{\nu,s} \left[ k_{f,\nu,s}^p E_f^p + \left( \sqrt{M^{*2} + 2\nu eB} - s\kappa_p B \right)^2 \ln \left| \frac{k_{f,\nu,s}^p + E_f^p}{\sqrt{M^{*2} + 2\nu eB} - s\kappa_p B} \right| \right], \quad (2.2)$$

$$\begin{aligned} \varepsilon_n = & \frac{1}{4\pi^2} \sum_s \left\{ \frac{1}{2} k_{f,s}^n E_f^{n3} - \frac{2}{3} s\kappa_n B E_f^{n3} \left( \arcsin \frac{M^* - s\kappa_n B}{E_f^n} - \frac{\pi}{2} \right) - \left( \frac{s\kappa_n B}{3} + \frac{M^* - s\kappa_n B}{4} \right) \times \right. \\ & \left. \left[ (M^* - s\kappa_n B) k_{f,s}^n E_f^n + (M^* - s\kappa_n B)^3 \ln \left| \frac{k_{f,s}^n + E_f^n}{M^* - s\kappa_n B} \right| \right] \right\}, \end{aligned} \quad (2.3)$$

$$\varepsilon_e = \frac{eB}{4\pi^2} \sum_{\nu,s} \left[ k_{f,\nu,s}^e E_f^e + \left( \sqrt{m_e^2 + 2\nu eB} - s\kappa_e B \right)^2 \ln \left| \frac{k_{f,\nu,s}^e + E_f^e}{\sqrt{m_e^2 + 2\nu eB} - s\kappa_e B} \right| \right], \quad (2.4)$$

$$\varepsilon_\mu = \frac{eB}{4\pi^2} \sum_{\nu,s} \left[ k_{f,\nu,s}^\mu E_f^\mu + \left( \sqrt{m_\mu^2 + 2\nu eB} - s\kappa_\mu B \right)^2 \ln \left| \frac{k_{f,\nu,s}^\mu + E_f^\mu}{\sqrt{m_\mu^2 + 2\nu eB} - s\kappa_\mu B} \right| \right], \quad (2.5)$$

where  $\nu = 0, 1, 2, 3, \dots$  denotes the Landau levels for charged particles. The summation of  $\nu$  starts from 0(1) for spin-up protons (leptons), and  $\nu$  runs up to largest integer for which the Fermi momentum squared  $k_{f,\nu,s}^2$  is positive. The energy density of neutron star matter can be expressed as

$$\varepsilon = \varepsilon_p + \varepsilon_n + \varepsilon_e + \varepsilon_\mu + \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\rho^2 \rho_{30}^2 + 3\Lambda_\nu g_\rho^2 \rho_{30}^2 g_\omega^2 \omega_0^2 + \frac{\zeta}{8} g_\omega^2 \omega_0^4. \quad (2.6)$$

The nucleons and leptons satisfy the chemical equilibrium condition  $\mu_n - \mu_p = \mu_e = \mu_\mu$  and charge neutrality condition  $\rho_p = \rho_e + \rho_\mu$ .

### 3 Density dependent symmetry energy

First of all, we investigate the properties of nuclear matter (without leptons) in magnetic field with the inclusion of the nucleon AMM. As shown in Fig. 1, the energy per nucleon of asymmetric nuclear matter versus  $\beta^2$  still fulfills the parabolic law for the selected densities, i.e.,  $\rho_0$ ,  $2\rho_0$ ,  $3\rho_0$  and  $5\rho_0$ , where  $\rho_0 = 0.16 \text{ fm}^{-3}$  is the saturation density. As expected, increasing the magnetic field the energy per particle turns out to be increasing lower, especially at low densities. In fact, the Landau quantization of the charged particles causes a softening of the equation of state (EOS), as already found in Ref. [13]. At large densities such as  $\rho = 5\rho_0$ , as the softening of the EOS by the Landau quantization will be gradually overwhelmed by the stiffening resulting from the AMM effect [39, 40], the energies are slightly reduced by a strong magnetic field. In addition, it is found that the more neutron-rich the dense matter is, the weaker of changes the magnetic field causes. This is simply explained by the fact that neutrons carry no charge so that they have no Landau levels to fill. The direct coupling of neutrons to magnetic field is just due to the neutron AMM. For protons, however, their charge strongly couples with the magnetic field, forming the Landau levels, and this coupling is much stronger than the direct coupling between the AMM and magnetic field. Since the  $\beta^2$  law still holds in magnetic field below  $10^5 B_c^e$ , the symmetry energy can be obtained just as the field-free case. The influences of the proton and neutron AMM on the energy per nucleon  $E/A$  is illustrated in Fig. 2. The nucleon AMM lead to a reduction of  $E/A$  due to their coupling to the magnetic field. At low isospin asymmetry  $\beta$ , the proton AMM contributes more sizeably than the neutron AMM, because the coupling between the proton AMM and the magnetic field leads to a non-negligible change in the filling of Landau levels and hence the energy spectra. At high isospin asymmetry, the effect of the neutron AMM is larger than that of the proton AMM because of the large neutron fraction.

In the upper panel of Fig. 3, we plot the density dependence of the symmetry energy for various magnetic field strengths with the inclusion of AMM. The employed RMF interaction is FSU-Gold [25]. Other interactions with some modifications of  $\Lambda_\nu$  and  $g_\rho$  based on FSU-Gold [41] do not lead to very different results. The density-dependent symmetry energy is enhanced in strong magnetic field, in particular at low densities. Whereas the effect of the magnetic field is rather weak below  $5 \times 10^4 B_c^e$ . As we mentioned above, the energy per particle of the neutron is reduced more slightly than that of proton. Therefore, the symmetry energy, defined as the energy per particle difference between pure neutron matter and symmetric matter, gets enhanced, with the effect of changing the fraction of each component. To show the shift of the symmetry energy due to the

nucleon AMM, we report in the lower panel of Fig. 3 the symmetry energy of the nuclear matter in a magnetic field with and without the AMM in calculations. It can be seen that the effect of the proton AMM is what we expected while the one of the neutron AMM is much weaker, as one can easily realize from the results of Fig. 2 and the corresponding comments.

## 4 Fractions of each component in the neutron star matter

The proton fractions  $Y_p$  and muon fractions  $Y_\mu$  for  $\beta$ -stable dense matter are displayed in Fig. 4 as a function of the magnetic field strength under different densities. The neutron and electron fractions are obtained via the relations  $Y_n = 1 - Y_p$  and  $Y_e = Y_p - Y_\mu$ . The interactions with some modifications of  $\Lambda_v$  and  $g_\rho$  based on FSU-Gold [41] which scan different behavior of symmetry energy from very stiff ( $\Lambda_v = 0.00$ ) to very soft ( $\Lambda_v = 0.04$ ), are employed in calculations. It can be found that the proton and muon fractions remain unaltered compared with the field-free case for relatively weak magnetic fields. At the saturation density, the proton fractions (and muon fractions) are not very different from each other, because the symmetry energy either soft or stiff, takes a value in agreement with the empirical one. However, with increasing density, this difference becomes sizable. The stiffer the symmetry energy is, the larger the proton and muon fractions are. As soon as the magnetic field becomes strong enough, such as  $B > 2 \times 10^4 B_c^e$ , those fractions depend obviously not only on the symmetry energy but also on the magnetic field strength at a given density. And the proton and muon fractions rapidly bend up starting from a certain value of the magnetic field. Beyond this threshold, the charged particles are completely spin polarized due to Landau quantization with the Fermi energies considerably reduced. This threshold is, for instance,  $B = 5 \times 10^4 B_c^e$  at  $\rho = 0.16 \text{ fm}^{-3}$  for the proton fraction. At the higher density matter, a much stronger magnetic field is required to reach the threshold. Besides, the interaction giving a stiff symmetry energy displays a larger threshold, which stems from the fact that the stiff symmetry energy provides a large proton fraction and hence a high proton density at a given nucleon density. In a word, the fraction of each component of the neutron star matter depends on both the density-dependent symmetry energy and the magnetic field strength. For the field-free case, the threshold for URCA process is that the proton fraction reaches about 11% at low densities. At high densities, when muons are involved, this threshold becomes density dependent and can reach about 14% [42]. But for the dense matter in magnetic field, as show in Ref. [17], the magnetic field smears out the threshold between the open and closed direct URCA regimes producing magnetic broadening of

the direct URCA threshold. When  $p_{Fn} < p_{Fp} + p_{Fe}$ , the direct URCA process is open, and when  $p_{Fn} > p_{Fp} + p_{Fe}$  that is forbidden at field free case the direct URCA process can be still open if magnetic field is included. In order to study the effects of the AMM of each particles on the proton and muon fractions, Fig. 5 presents the  $Y_p$  and  $Y_\mu$  as a function of magnetic field strength with and without the AMM, taking the  $\beta$ -stable matter at  $\rho = \rho_0$  as an example. The proton AMM gives the biggest contribution compared to the AMM of other constituents. The muon AMM almost has no effect on the fraction of each component because of its large mass (small magnetic moment) and low fraction. The electron and neutron AMM affect the fractions at rather strong magnetic field with nearly the same amplitude, which is not obvious. The effect of the proton AMM is evident because it is able to affect the filling of Landau levels and hence the corresponding fraction.

## 5 Spin polarization of nucleons in neutron star matter

It is worthwhile discussing the spin polarization of neutrons and protons in  $\beta$ -stable neutron star matter under the strong magnetic field. The spin polarization of protons and neutrons in fact can influence the superfluidity of neutron stars and, as a consequence, its rotational dynamics and the cooling. The nucleon spin-polarization is defined as

$$S_\tau = \frac{\rho_{\tau\uparrow} - \rho_{\tau\downarrow}}{\rho_\tau}, \quad (5.7)$$

with  $\tau = p, n$ . When no AMM is included, only proton spin polarization may occur because the coupling between charge and magnetic field survives and obviously affects the single particle spectrum. At the critical field, all protons occupy the first Landau level so as to reach full spin polarization. But when their AMM are included, the energy spectra for both protons and neutrons are spin dependent, and hence the neutrons can also experience spin polarization for the coupling between their AMM and the magnetic field. Since this coupling is much weaker than that between charged particle and magnetic field, the complete polarization of neutrons requires a much stronger magnetic field, as discussed in Ref. [13]. Fig. 6 illustrates the spin polarization of protons and neutrons with the inclusion of AMM adopting the same interactions as in Fig. 4. The behavior of  $S_p$  and  $S_n$  results from the interplay between the magnetic field intensity and the density dependent symmetry energy. Both increase (in absolute value) as increasing magnetic field for any density. At a larger density, it requires a stronger magnetic field for proton to be fully spin polarized. In other words, the proton becomes more difficult to be polarized as the density increases. In addition, the larger the symmetry energy is, the less protons can be polarized. This phenomenon can be

explained as follows. A larger symmetry energy may lead to a less neutron-rich dense matter, namely, a larger fractions of protons in  $\beta$ -stable matter. Yet, the protons in higher density is more difficult to be polarized, as shown in upper panel in Fig. 6. The spin polarization of neutrons is almost insensitive to the symmetry energy, owing to the weak coupling between neutrons and magnetic field.

Fig. 7 displays the AMM effect on the spin polarizations of protons (upper panel) and neutron (lower panel) taking the  $\beta$ -stable matter at  $\rho = \rho_0$  as an example. The results with only the lepton AMM and without any AMM completely coincide with each other, indicating that the lepton AMM do not affect the spin polarizations of nucleons. The proton AMM contributes most dominantly to the spin polarizations of the proton since this AMM affects the filling of Landau levels for protons. The neutron, if their AMM are neglected, can not be polarized at all as shown in the lower panel. After the AMM of neutron is taken into account, the doubly degeneracy with opposite spin projections is destroyed and hence the neutrons show the spin polarization.

## 6 Summary

The properties of dense matter in strong magnetic fields, including the density- dependent symmetry energy, chemical composition and spin polarizations have been studied within the relativistic mean field model FSU-Gold. The magnetic field does not modify the parabolic behavior of the energy per particle in asymmetric matter at least in the range of the magnetic field considered in this work, and hence the symmetry energy can be derived just as the field-free case. It is found that the strong magnetic field leads to an enhancement of the symmetry energy with respect to field free case, in particular at low densities. The fraction of each component has been calculated with some modified FSU-Gold interactions that can provide both stiff and soft symmetry energy. Once the magnetic field is strong enough, the fractions of components are sensitive to both the symmetry energy and the strong magnetic field. The density-dependent symmetry energy affects the proton polarization but it has almost no effect on neutron polarization. Moreover, the effects of the AMM on the energy per nucleon, the symmetry energy, fractions and spin-polarization were analyzed. The corresponding effects on the symmetry energy and the fractions of each component almost determined by the proton AMM, and the spin polarizations of the protons (neutrons) are dominated by the proton (neutron) AMM.



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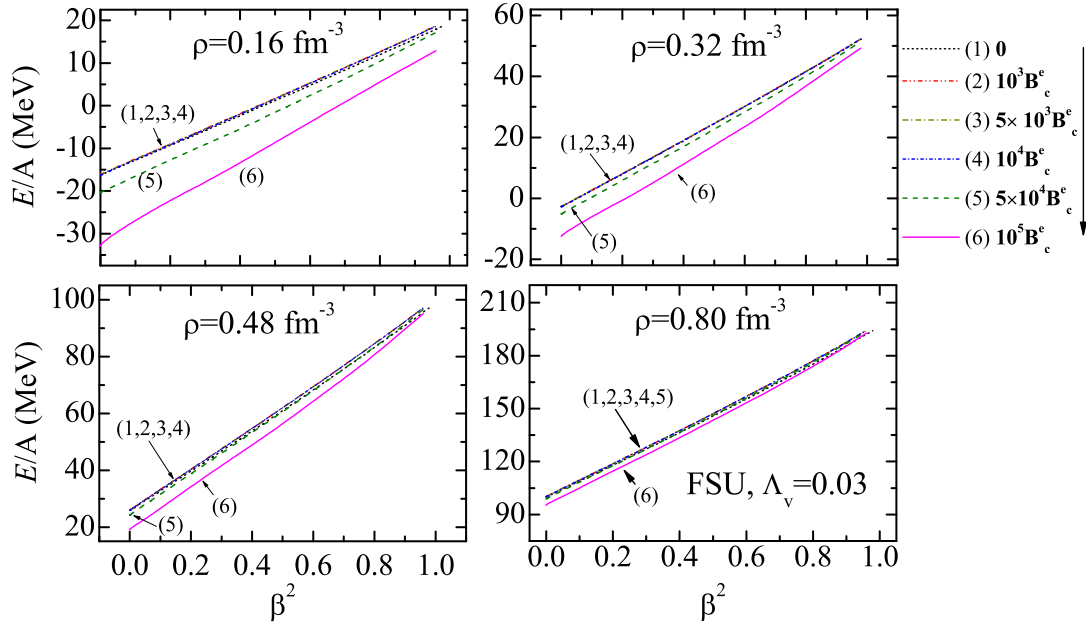


Figure 1: (Color online) The energy per nucleon  $E/A$  as a function of  $\beta^2$  for different values of the magnetic field  $B$ , where  $\beta$  is asymmetry. The RMF interaction FSU-Gold with  $\Lambda_v = 0.03$  is used.

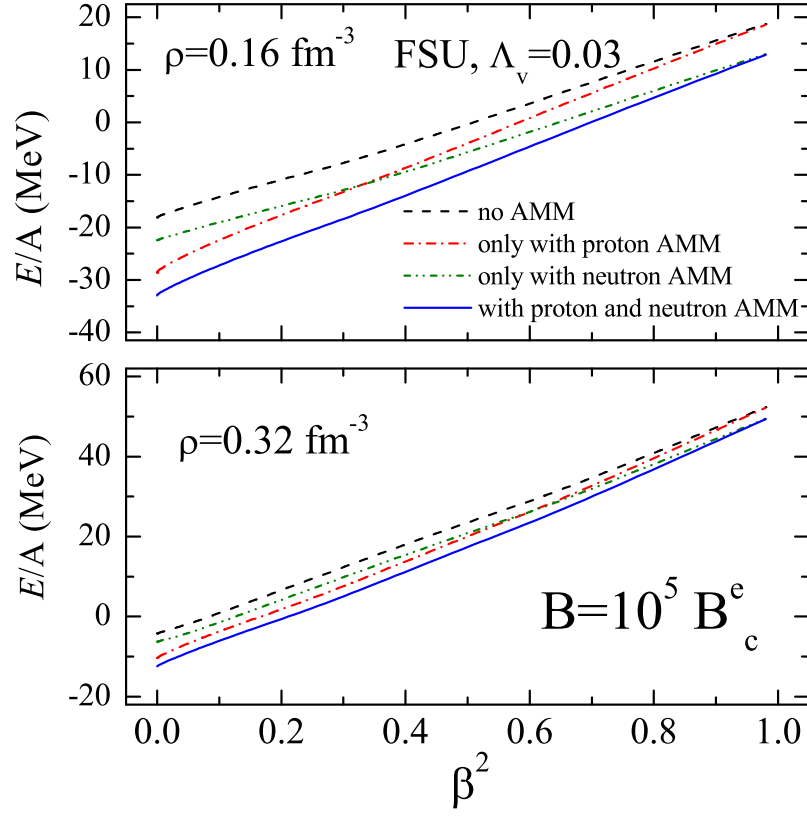


Figure 2: (Color online) Effects of the nucleon AMM on the energy per nucleon  $E/A$  of asymmetric nuclear matter in a magnetic field of  $10^5 B_c^e$ . The interaction FSU-Gold with  $\Lambda_v = 0.03$  is used.

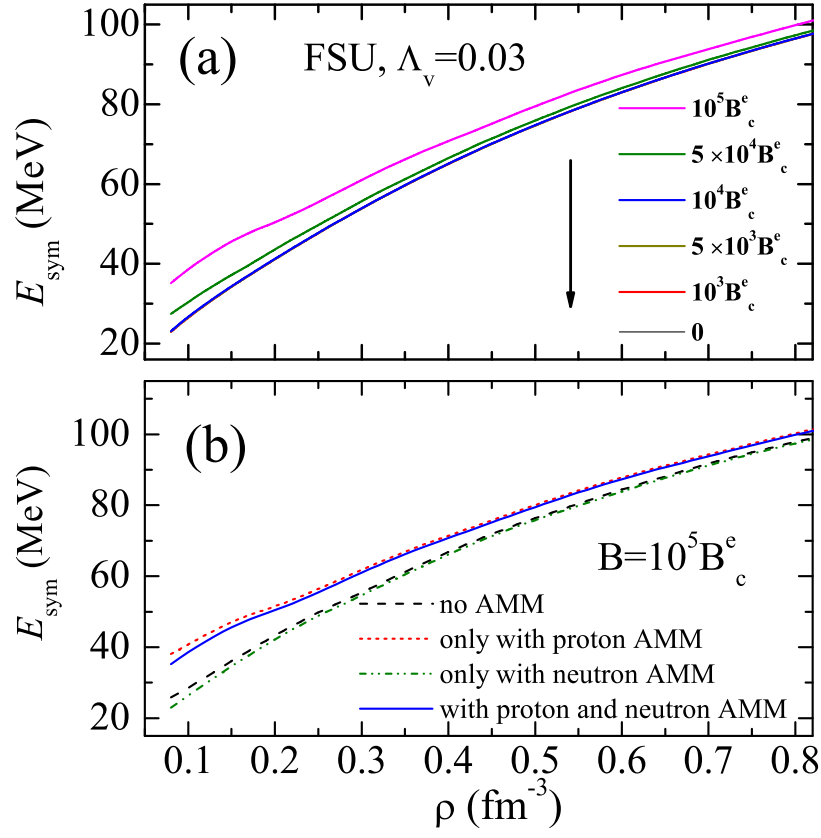


Figure 3: (Color online) (a) Density dependence of the nuclear symmetry energy for different magnetic field strengths. (b) Effects of the AMM on the symmetry energy of nuclear matter in a magnetic field of  $10^5 B_c$ . The interaction FSU-Gold with  $\Lambda_v = 0.03$  is used.

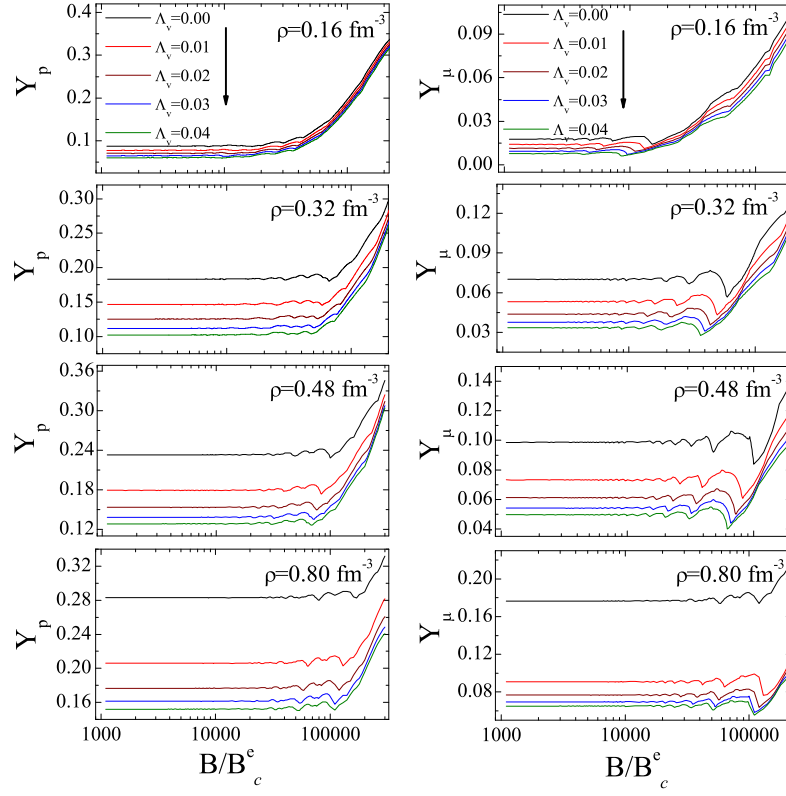


Figure 4: (Color online) Proton and muon fractions in  $\beta$ -stable matter versus the magnetic field strength  $B$  under different density  $\rho$ . The calculations are performed with modified FSU-Gold interactions [41] providing stiff ( $\Lambda_v = 0.00$ ) to soft ( $\Lambda_v = 0.04$ ) symmetry energy.

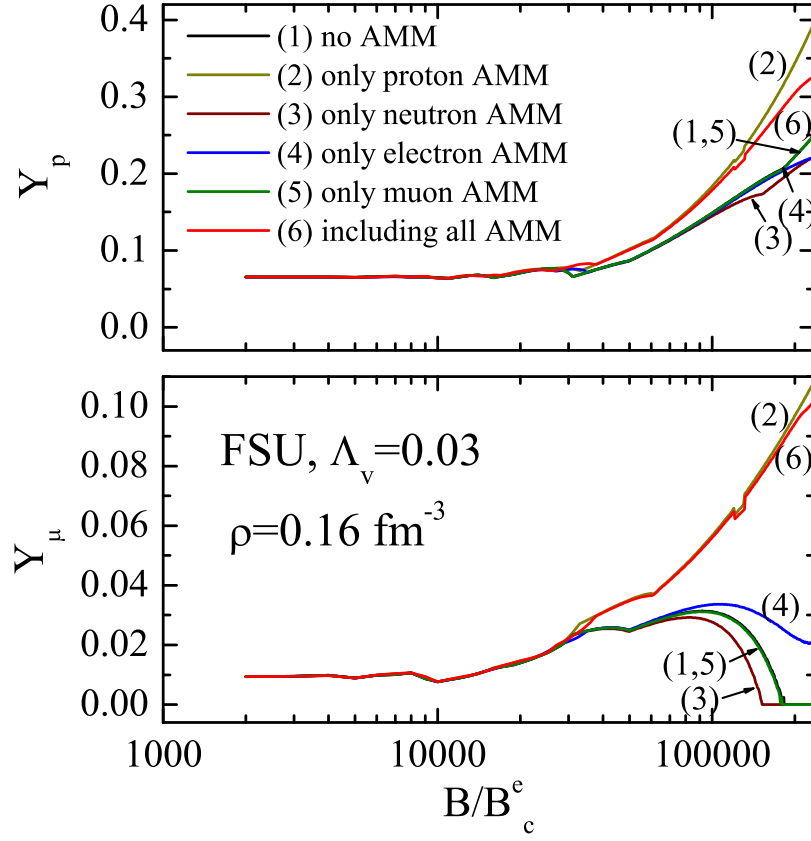


Figure 5: (Color online) Effect of the AMM of each component on the proton and muon fractions in  $\beta$ -stable matter versus the magnetic field strength with the interactions FSU-Gold ( $\Lambda_v = 0.03$ ), taking the density  $\rho = \rho_0$  as an example.



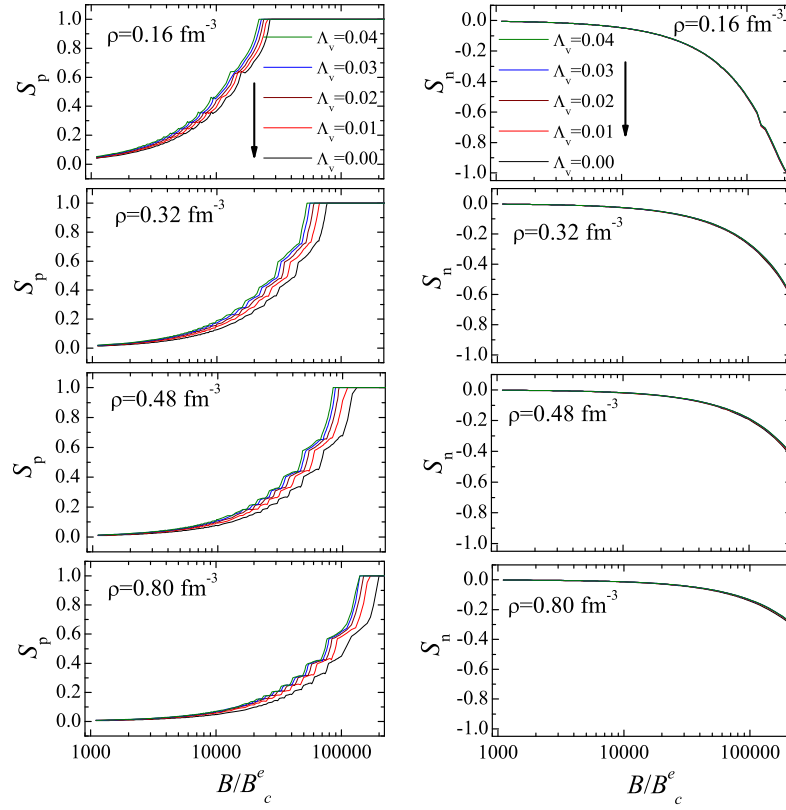


Figure 6: (Color online) Spin polarization of protons and neutrons in  $\beta$ -stable matter as a function of the magnetic field strength  $B$  under different density  $\rho$ . The calculations are performed with modified FSU-Gold interactions [41] providing stiff ( $\Lambda_v = 0.00$ ) to soft ( $\Lambda_v = 0.04$ ) symmetry energy.

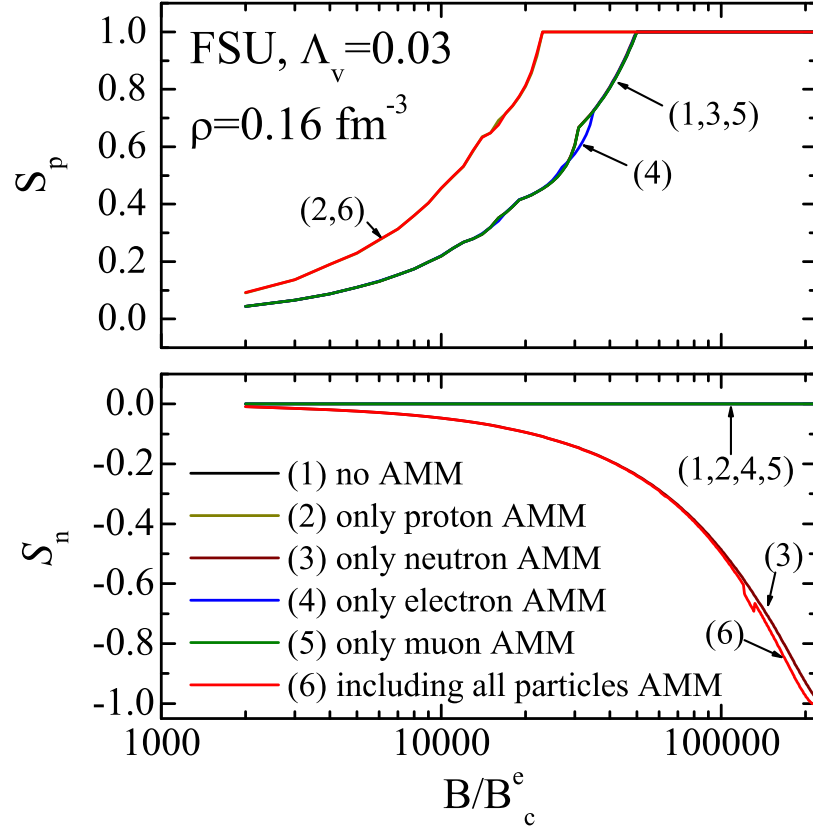


Figure 7: (Color online) Effect of the AMM of each component on the spin polarization of protons and neutrons as a function of the magnetic field strength with the interactions FSU-Gold  $\Lambda_v = 0.03$ , taking the  $\beta$ -stable matter at the density  $\rho = \rho_0$  as an example.